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SPECIAL FEATURE: ORIGINAL ARTICLE

Social-ecological systems on walleye pollock under changing environment: Inter-disciplinary approach

Straddling the line: cooperative and non-cooperative strategies for management of Bering Sea pollock

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Abstract The eastern Bering Sea fishery for pollock, *Theragra chalcogramma*, yields a first wholesale value over \$1 billion; it is the premier US fishery. While there is general agreement that this fishery is managed under principles that foster sustainability, the stock is not wholly contained within the US Exclusive Economic Zone. Management of straddling stocks can be highly contentious, particularly when, as is the case for pollock, the spatial distribution varies considerably. When the center of pollock abundance shifts to the northwest, an increased portion of the stock is exposed to harvest by vessels operating in the Russian Federation Exclusive Economic Zone. The lack of coordination in the management of this transboundary stock presents a risk that is not reflected in current management strategies. We use a multiple product/multiple market bioeconomic model to characterize optimal cooperative and non-cooperative harvest management strategies from the perspective of US and Russian pollock fisheries under environmentally induced changes in pollock abundance and the distribution of that abundance.

Keywords Sustainable fisheries · Straddling stock · Game theory

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Introduction

Fluctuations in the abundance and distribution of exploited species reflect latent processes that govern intra- and inter-species dynamics, the conduct of fisheries, and the influence of variations in abiotic factors. For example, statistically significant intertemporal relationships have been observed between environmental factors and recruitment, growth, mortality, and the abundance of pollock. Correlated recruitment patterns across a suite of North Pacific species, including pollock, has been construed as evidence of environmental forcing [1]. Significant correlations have been reported for time series of eastern Bering Sea (EBS) pollock recruitment (and residuals of a Ricker spawner-recruit relationship) and 1-year lagged time series of annual air temperature, ice cover, and bottom temperature anomalies [2]. Multi-annual variation in the spatial distribution of EBS pollock is related to avoidance of the cold pool, a persistent bottom water feature that develops on the EBS shelf as a function of sea ice extent [3]. Variations in the timing of sea ice retreat is hypothesized to cause oscillation between bottom-up and top-down control mechanisms as determinants of recruitment success [4]. This suggests that time series of recruitments will demonstrate long-period serial correlations reflective of multi-annual correlations in sea ice extent and the timing of sea ice retreat, and short-period serial correlations reflective of within-year relationships between the springtime sea ice retreat and overwinter survival [5]. The center of distribution of sub-arctic species, including EBS pollock, has been shown to reflect a climate change signal superimposed on multiannual variation in sea ice extent [6]. Even though EBS pollock is a subarctic species, complexities in control mechanisms are shown to reduce recruitment success when mean July–September sea surface temperatures exceed 8.5 °C [7].

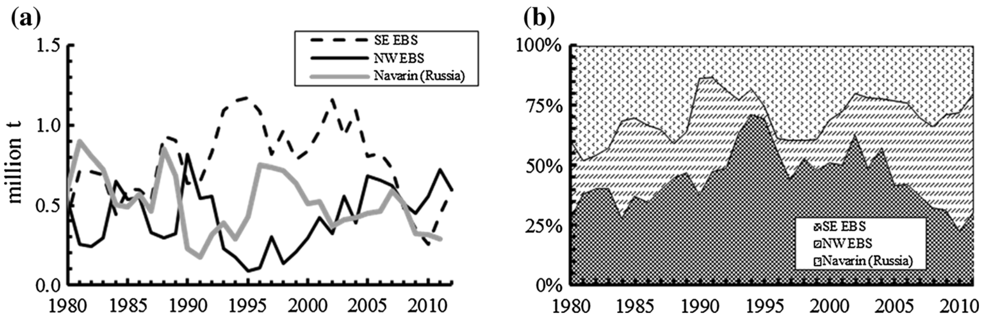

Fig. 1 Pollock catches from the US EBS and Russian Navarin regions in **a** million *t* and **b** percentages. SE EBS and NW EBS refer to catches taken in the US EBS to the east and west of 170°W. Russian Navarin refers to Russian catches east of 170°E to the Russian–US boundary line. US EBS data are from Ianelli et al. [8]; Russian data are from the 17th Annual Conference of the Parties to the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea

Inter-annual variances of pollock catches in the Navarin region (Russian EEZ portion of the Bering Sea), the NW EBS (US EEZ catches west of 170 W), and the SE EEZ (US EBS catches east of 170 W) are consistent with underlying environmental forces (Fig. 1). The data indicate a statistically significant ($p < 0.01$) inverse relationship ($r = -0.59$) consistent with periodic shifts in the spatial distribution of EBS pollock between the SE and NW. A similar inverse relationship exists between US and Russian catches in the Bering Sea with $r = -0.49$ at a statistically significant level ($p < 0.01$). (See Figure 1.2 and 1.4 in Ianelli et al. [8] for GIS plots of catches during the EBS pollock A (January–May) and B (June–December) seasons for 2010, 2011, and 2012).

These geographic shifts affect the profitability of the EBS pollock fishery and the magnitude of benefits that accrue to communities that are associated with the fishery. In addition, changes in input prices (e.g., fuel costs), regulatory systems, and technology influence the magnitude and distribution of benefits between sectors within the fishery and among communities that support those sectors. For example, shifts in the magnitude of pollock to the NW increase fuel costs and disproportionately affect those fishermen with smaller vessels. This, in turn, affects the Western Alaskan communities that derive economic benefits from ownership and employment within the fishery [9].

To fully appreciate the character of these impacts, it is important to understand how the fishery developed and evolved. In brief, the EBS pollock fishery began in earnest in the 1960s, with harvests taken mostly by distant-water fleets from Japan and the USSR. With adoption of the Fisheries Conservation and Management Act (FCMA) of 1976, the US asserted management authority over fishery resources within a 200-mile EEZ. Among other provisions, the FCMA stipulated the development of Fishery Management Plans for all fishery stocks within the EEZ and indicated a preference for developing domestic fisheries even if so doing entailed displacement of foreign fisheries. These measures, coupled with the decline of crab fisheries, stimulated a rapid increase in domestic harvesting capacity such that by the mid-1980s, foreign fishing allocations were suspended and the fishery consisted almost entirely of joint-ventures that paired domestic harvesting vessels with foreign owned motherships and foreign-controlled processing plants. The latter half of the 1980s saw the development and demise of a pollock fishery in the central Bering Sea, which provided fishing opportunities for foreign vessels displaced from the US. The latter half of the 1980s also saw the rapid development of domestic catcher-processors, continued expansion of the fleet of domestic catcher vessels, and rapid expansion of shore-based processing plants. By 1991, domestic fishing had entirely displaced joint ventures and the fishery was becoming increasingly over-capitalized in harvesting and processing capacity. The outcome of excess capacity was a race-for-fish that engendered economic stress and political gridlock in the management arena. Temporary measures intended to stabilize catch allocations to inshore and offshore fleets did nothing to stem the influx of harvesting capacity and expansion of processing capacity within those sectors and consequently did not eliminate the race-for-fish or ease the financial distress of fishing and processing firms. All that changed in 1999 as a result of implementation of the American Fisheries Act (AFA) which set a permanent moratorium on entry of new vessels into the fishery, mandated retirement of several catcher processors, created permanent allocations to each sector, and empowered those sectors to form cooperatives with authority to contract shares of the sector allocations to cooperative members [10, 11].

The governance and industrial organization of pollock fisheries in the US EEZ differs markedly from that of the Russian Federation EEZ pollock fisheries. Under the AFA, the US fishery has operated under a rights-based governance structure that has allowed firms to form cooperatives to contractually sub-allocate shares of the total allowable catch (TAC) to individual vessels [11]. In contrast, the governance of Russian Federation EEZ fisheries has remained in flux with ever-changing rules about the duration of catch quotas, whether the quotas can be held by foreign nationals or figurehead corporations, and the extent of processing required prior to export [12]. While the US EEZ pollock fishery has become highly capitalized, very profitable, and geared to value-added production, conditions in the Russian Far East have not been conducive to investment needed to modernize fishing or processing capital. Thus, substantial portions of Russian catches have served as minimally processed inputs for value-added production by Chinese reprocessors. The lack of investment in modern processing technology means that the same volume of fish harvested from Russian Federation EEZ waters yields a lower quality and lesser quantity of product than it would yield if harvested in the US EEZ. These effects are exacerbated to the extent that the portion of the eastern Bering Sea pollock stock that distributes into the Russian EEZ consists of disproportionate numbers of younger fish, thus naturally yielding lower recovery rates and less valuable product forms.

In addition, although there has been an extensive history of joint research activities by Russian Federation and US fisheries scientists, there remains considerable uncertainty regarding relationships among pollock in the EBS, central Bering Sea, Aleutian Islands, and Navarin basin regions as well as how that structure shifts through time both within and between years [13]. This paper does not resolve that ambiguity but instead examines the implications of alternative management strategies in the face of uncertainty about stock structure and the role of climate-induced changes in the distribution of pollock.

Management of transboundary fish stocks has been characterized as a two-party game [14–17]. Solutions to two-party games depend on the extent to which each party engages in strategic behavior. Quasi-competitive behavior represents an extreme under which each party endeavors to set a harvest management strategy that ignores the strategies that might be adopted by the other party. In the case of the Bering Sea pollock fishery, the current approach to fishery management can be characterized as quasi-competitive: the US does its thing, the Russians do theirs, and each pretends to harvest stocks that do not migrate or diffuse across the convention line. Under collusive management strategies, parties seek to optimize their joint product. In the context of Bering Sea pollock, this would amount to the US and Russian Federation agreeing to a joint management strategy to maximize the total net benefits of harvests without concern about the distribution of benefits between nations. Under Cournot-Nash or Stackelberg management strategies, each nation recognizes that their individual benefits are conditional on the other nation's choices, but they stop short of collusion. For example, in Dockner et al. [18], the parties are assumed to recognize that they share oligopoly power in the output markets. That is they recognize that the prices they receive in output markets depend on their own decisions about harvest levels as well as the other party's harvest level decisions. In the case of Bering Sea pollock, these solutions represent recognition that there are externalities associated with harvest management strategies independently adopted by the US and the Russian Federation and that the optimal choice of a management strategy for the US EEZ pollock fishery will depend on the management strategy that the Russian Federation adopts, and vice versa. Moreover, the choice of optimal strategy will vary as a function of: variations in stock abundance and the distribution of the stock; the relative value of product, product recovery rates, and differences in the magnitude of harvesting and processing costs; the enforceability of catch limits at fishery and individual participant levels; the character of governance regimes, etc.

While the structure of two-party games is conceptually simple, their solutions can be surprising. For example, based on a bioeconomic simulation, Lee et al. [19] concluded that it was optimal for the US to follow a conservative harvest strategy for Atlantic swordfish even though US catches are a small share of the total catch. The benefits of US adherence to a conservative harvest strategy were manifested in population growth, and while foreign nations were found to capture the lion's share of the benefits of US conservatism, the gains to US fishermen were nevertheless sufficient to warrant unilateral adoption of a conservative harvest strategy. Similarly, Kaitala and Pohjola [20] show that transfer payments can be used to encourage cooperative solutions that can lead to the optimal recovery of overharvested transboundary stocks.

This paper examines optimal harvest solutions under cooperative and non-cooperative management strategies for EBS pollock. Those solutions are contrasted with management structures currently employed for other natural resources that are also shared among multiple users. Understanding how property rights evolve in response to structural changes (such as changing technologies and climate change) to capture additional rents is important in considering the future gains which can be achieved through these optimal solutions.

Materials and methods

The bioeconomic model consists of four systems of matrix equations and an objective function that optimizes sustainable yields similar to the model structure used in [21].

The first set of matrix equations includes a three-region delay-difference model of pollock biomass with additional equations to represent female spawning biomass, recruitment, and an error correction model to account for the influence of contemporaneous and lagged environmental factors and the contemporaneous and lagged correlation among the residuals of the other three elements of the biological model. The second model component is a representation of harvest control rules that govern US and Russian Federation catches of pollock. The third component is a sector-specific model of domestic and international demand for pollock roe, surimi, fillets, and headed-and-gutted fish (H&G), and the allocation of those products to markets in the US, Japan, EU, Russian Federation, and China. The final component is a representation of how changes in sector specific input factor costs vary as a function of variations in fuel price, mean distance travelled to fishing grounds, and catch per unit effort (CPUE).

Population dynamics model

Equation (1) represents the 3×1 vector of age-3+ pollock biomass, $\mathbf{x}_t = \begin{pmatrix} x_t^{\text{se}} & x_t^{\text{nw}} & x_t^{\text{rf}} \end{pmatrix}'$, in the southeast (se) and northwest (nw) portions of the US eastern Bering Sea management area and in Russian Federation (rf) portions of the Bering Sea from 170°E to the US–Russian Federation Convention Line:

$$\mathbf{x}_t = \mathbf{a}_0 + \mathbf{A}_1\mathbf{x}_{t-1} + \mathbf{x}_{t-1}^{\Delta}\mathbf{A}_2\mathbf{x}_{t-1} + \mathbf{A}_3\mathbf{h}_{t-1} + \mathbf{A}_4\mathbf{r}_t + \boldsymbol{\varepsilon}_t. \tag{1}$$

The matrix $\mathbf{x}_{t-1}^{\Delta}$ is a diagonal matrix composed of the elements of lagged values of $\mathbf{x}_t$. Harvests of age-3+ pollock biomass for the same three regions are represented by $\mathbf{h}_t$. Recruitment, $\mathbf{r}_t$, is the production of age-1 pollock in each region. The coefficient vector $\mathbf{a}_0$ consists of the intercepts to the individual equations included in Eq. (1). The coefficients in $\mathbf{A}_1$ represent the effects of growth, natural mortality, and net migration, those in $\mathbf{A}_2$ represent density dependent effects in growth and net migration, those in $\mathbf{A}_3$ represent the effect of harvest mortality on current abundance across regions, while the coefficients in $\mathbf{A}_4$ distribute recruitment among the three regions. The coefficient matrices may be saturated or sparse, depending on the importance of spatial linkages. The error vector, $\boldsymbol{\varepsilon}_t$, is characterized by serial correlation within and across equations.

Female spawning biomass, $\breve{\mathbf{x}}_t$, is modeled in Eq. (2) as a stochastic function of age-3+ biomass:

$$\breve{\mathbf{x}}_t = \mathbf{B}\mathbf{x}_t + \boldsymbol{\upsilon}_t, \tag{2}$$

where off-diagonal terms in $\mathbf{B}$ allow for net migration of mature females. Like the coefficient matrices in Eq. (1), $\mathbf{B}$ could be saturated or sparse. The error vector, $\boldsymbol{\upsilon}_t$, reflects contemporaneous and serial correlation within and across equations.

Following Criddle and Havenner [22] as extended to a multivariate case in May [23], recruitment to the EBS pollock stock is represented in Eq. (3) as a vector time series that depends on the weighted lagged contribution of female spawners from the three regions:

$$\mathbf{r}_t = \boldsymbol{\Lambda}_0\breve{\mathbf{x}}_{t-l} + \breve{\mathbf{x}}_{t-l}^{\Delta}\boldsymbol{\Lambda}_1\breve{\mathbf{x}}_{t-l} + \boldsymbol{\eta}_t. \tag{3}$$

The coefficient matrices $\boldsymbol{\Lambda}_0$ and $\boldsymbol{\Lambda}_1$ represent the contribution of lagged female spawning biomass in each region to EBS pollock recruitment in each region in year t. Because the error, $\boldsymbol{\eta}_t$, reflects the influence of unmodeled lags, it is autocorrelated and may be contemporaneously correlated across regions as well as with the errors in Eqs. (1) and (2).

The last group of matrix equations (Eq. 4) in the population dynamics model is a state space time series error correction process that filters the residuals of Eqs. (1), (2), and (3) against patterns of environmental variation:

$$\begin{aligned} \begin{pmatrix} \boldsymbol{\varepsilon}_t & \boldsymbol{\upsilon}_t & \boldsymbol{\eta}_t & \mathbf{Env}_t \end{pmatrix}' &= \mathbf{D}_1\mathbf{z}_t + \mathbf{e}_t \\ \mathbf{z}_{t+1} &= \mathbf{D}_2\mathbf{z}_t + \mathbf{D}_3\mathbf{e}_t. \end{aligned} \tag{4}$$

The first of this pair of equations, the observation equation, maps the residuals from Eqs. (1), (2), and (3) and a vector of environmental time series into a set of latent state variables, $\mathbf{z}_t$. The second equation, the state equation, characterizes dynamic relationships within and between the state variables. The method used to construct the state variables and estimate the coefficients in $\mathbf{D}_1$, $\mathbf{D}_2$, and $\mathbf{D}_3$ is designed to augment lagged relationships to first-order in the states. Additionally, it minimizes the number of coefficients needed to represent system dynamics and ensures that $\mathbf{e}_t$ is a white noise process shared by the state and observation equations [24]. Because the residuals from Eqs. (1), (2), and (3) include serial correlations and reflect the influence of unmodeled environmental correlations, the coefficient estimates from independent estimation of those equations will be biased. However, Eqs. (1) through (4) can be iterated to achieve efficient estimates [22].

Different conjectures about the nature of biological linkages can be represented by constraints on coefficients in this system of matrix equations. For example, diagonal coefficient matrices represent independent stocks while block diagonal coefficient matrices represent stock groupings, and triangular coefficient matrices represent spatial hierarchical linkages between stocks. Model structure can be determined by sequential testing of restrictions based on the effect of those restrictions on the value of the sum of squared errors, AIC, BIC, Wald statistics, etc. Where there are insufficient observations to support estimation of the full model, restrictions can be imposed a priori and tested by sequential relaxation. In addition, the model can be estimated conditional on particular relationships among the stocks in the three regions to demonstrate the sensitivity of model outcomes to assumed relationships.

Harvest control rules

Harvest control rules serve two roles in the overall model. They serve as simple characterizations of current management strategies and they can be used to explore the likely performance of alternative management strategies. Both the Russian Federation and the US set harvest limits based on information about current stock biomass and anticipated biomass trends. Although actual catches may differ from specified catch limits, it is assumed that fishermen will catch no more than the TAC.

The Russian Federation is assumed to set harvest limits as a fixed proportion of biomass:

$$h_t^{\mathrm{rf}} \le \alpha^{\mathrm{rf}} x_t^{\mathrm{rf}}. \tag{5a}$$

Where α^{rf} is assumed to be between 0.1 and 0.6.

The US is assumed to set harvest limits according to the Bering Sea and Aleutian Islands groundfish Fisheries Management Plan tier 1 harvest control rule which is illustrated by Fig. 2 [25]. Under this rule, the annual catch limit must be less than the acceptable biological catch, $h_{\mathrm{ABC}}^{\mathrm{us}}$, which must, in turn, be less than or equal to the overfishing limit, $h_{\mathrm{OFL}}^{\mathrm{us}}$. Formally, the rule is:

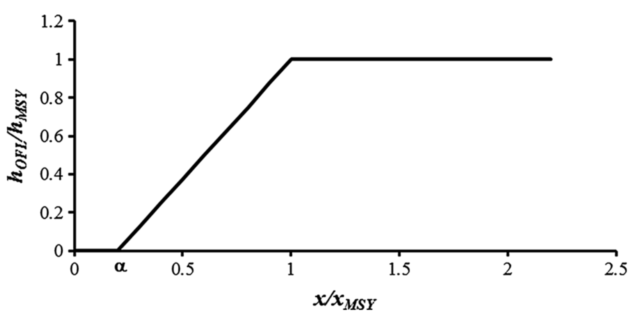

Fig. 2 US Bering Sea and Aleutian Islands groundfish Fisheries Management Plan tier 1 harvest control rule

Table 1 Harvest control rule for US EBS pollock

reference value	Stock status		
	$\frac{x_t}{x_{\mathrm{MSY}}} \le \alpha^{\mathrm{us}}$	$\alpha^{\mathrm{us}} < \frac{x_t}{x_{\mathrm{MSY}}} \le 1$	$1 < \frac{x_t}{x_{\mathrm{MSY}}}$
$h_{\mathrm{OFL}}^{\mathrm{us}}$	0	$\mu_{\mathrm{MSY}}\left(\frac{1}{1-\alpha^{\mathrm{us}}}\right)\left(\frac{x_t}{x_{\mathrm{MSY}}}-\alpha^{\mathrm{us}}\right)$	μ_{MSY}
$h_{\mathrm{ABC}}^{\mathrm{us}}$	0	$\breve{\mu}_{\mathrm{MSY}}\left(\frac{1}{1-\alpha^{\mathrm{us}}}\right)\left(\frac{x_t}{x_{\mathrm{MSY}}}-\alpha^{\mathrm{us}}\right)$	$\breve{\mu}_{\mathrm{MSY}}$

$$h_t^{\mathrm{us}} = h_t^{\mathrm{se}} + h_t^{\mathrm{nw}} \le h_{\mathrm{ABC}}^{\mathrm{us}} \le h_{\mathrm{OFL}}^{\mathrm{us}}, \tag{5b}$$

where the values for $h_{\mathrm{OFL}}^{\mathrm{us}}$ and $h_{\mathrm{ABC}}^{\mathrm{us}}$ are conditional on stock status (Table 1).

Where μ_{MSY} is the arithmetic mean of the probability density function (pdf) of estimates of maximum sustainable yield (MSY), $\breve{\mu}_{\mathrm{MSY}}$ is the geometric mean of the pdf of MSY, and α^{us} is between 0 and 1.

Market model

The market model is described in detail in Strong [26]. In brief, the model uses two matrix equations to describe transactions of finished products: fillets, surimi, roe, and H&G. The system of allocation equations can be represented by:

$$\mathbf{q}_t = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1\mathbf{p}_t + \boldsymbol{\beta}_2\mathbf{p}_{t-1} + \boldsymbol{\beta}_3\mathbf{q}_{t-k} + \boldsymbol{\beta}_4\mathbf{m}_t + \mathbf{u}_t. \tag{6}$$

The vector of quantities allocated from source to market, $\mathbf{q}_t$, includes fillets, surimi, roe, and H&G produced in the US and Russian Federation allocated to markets in the US, Japan, EU, Russian Federation, and China. These allocations are determined by current and lagged product prices, $\mathbf{p}_t$, in the US market, import prices in the EU, Japan, and China, and domestic prices in the Russian Federation. Allocations are also affected by lagged production, $\mathbf{q}_{t-k}$, and seasonality, $\mathbf{m}_t$. The random vector, $\mathbf{u}_t$, is contemporaneously correlated across product forms and with the random vector, $\boldsymbol{\xi}_t$, in Eq. (7). Because the markets are not fully integrated across product forms, the coefficient matrices, $\boldsymbol{\beta}_i$, are sparse.

The second system of market equations represents inverse demands for pollock products in the US, Japan, EU, Russian Federation, and China:

$$\begin{aligned}\mathbf{p}_t = {} & \boldsymbol{\gamma}_0 + \boldsymbol{\Gamma}_1\mathbf{q}_t + \boldsymbol{\Gamma}_2\mathbf{p}_t + \boldsymbol{\Gamma}_3\mathbf{p}_{t-1} + \boldsymbol{\Gamma}_4\mathbf{p}_t^{\mathrm{sub}} + \boldsymbol{\Gamma}_5\mathbf{Inv}_{t-1} \\ & + \boldsymbol{\Gamma}_6\mathbf{Inc}_t + \boldsymbol{\Gamma}_7\mathbf{Exch}_t + \boldsymbol{\Gamma}_8\mathbf{m}_t + \xi_t.\end{aligned} \tag{7}$$

Product prices are modeled as a linear function of product quantities, current and lagged prices of pollock products in other markets (the diagonal elements of $\boldsymbol{\Gamma}_2$ are zero), the price of substitute seafood products, $\mathbf{p}_t^{sub}$, inventories of pollock products, $\mathbf{Inv}_t$, income in consuming nations, $\mathbf{Inc}_t$, prevailing exchange rates, $\mathbf{Exch}_t$, and binary variables, $\mathbf{m}_t$, to represent seasonal variations in price. Because demands are not fully integrated across product forms, the coefficient matrices, $\boldsymbol{\Gamma}_j$, are sparse. The error vector, $\boldsymbol{\xi}_t$, for Eq. (7) includes contemporaneous and serial correlations due to the technological connections between catching and processing and relatedness between output factor prices.

The quantity of fillets, surimi, roe, and H&G produced is physically limited by the amount of pollock harvested and by a vector of product conversion rates, $\boldsymbol{\omega}$, which vary as a function of the size of pollock harvested, season, and technological innovation:

$$\mathbf{q}_t \leq \omega \mathbf{h}_t. \tag{8}$$

Total revenue from pollock production from fillets, surimi, roe, and H&G can be calculated from the solution to Eqs. (6), (7), and (8):

$$\mathrm{TR}_t = \mathbf{p}_t \mathbf{q}_t. \tag{9}$$

Production costs

There are three basic production modes for EBS pollock: catcher vessels that deliver chilled whole fish to shore-based processing plants (SS), catcher vessels that deliver to motherships — processing vessels that operate on the fishing grounds (MS), and catcher–processors — ships that process their own catches (CP). The average variable cost function represents production costs through to the first wholesale level. That is, it is structured to reflect fishing costs and cost of processing pollock into fillets, roe, surimi, and H&G product forms. Because we do not have ready access to information on the capital value of fishing vessels and processing plants or their amortization schedules, nor detailed information on operating costs, we focus on those costs that are both observable and affected by day-to-day operating decisions. These average variable costs, $\mathbf{c}_t$, are modeled as exponential (Cobb-Douglas) functions:

$$\begin{aligned} \ln(\mathbf{c}_t) &= \ln\left(\mathbf{c}_t^{\mathrm{fish}}\right) + \ln\left(\mathbf{c}_t^{\mathrm{proc}}\right) = \boldsymbol{\theta}_0 + \boldsymbol{\theta}_1 \ln\left(p_t^{\mathrm{fuel}}\right) \\ &\quad + \boldsymbol{\theta}_2 \ln(\mathrm{Dist}_t) + \boldsymbol{\theta}_3 \ln(\mathbf{CPUE}_t) + \boldsymbol{\theta}_4 \ln\left(\mathbf{L}_t^{\mathrm{fish}}\right) \\ &\quad + \theta_5 \ln\left(\mathbf{L}_t^{\mathrm{proc}}\right) + \boldsymbol{\theta}_6 \ln\left(p_t^{\mathrm{exv}}\right) + \boldsymbol{\theta}_7 \ln\left(p_t^{\mathrm{add}}\right) + \zeta_t \\ &= \Theta \mathbf{C}_t + \zeta_t, \end{aligned} \tag{10}$$

where $\mathbf{c}_t^{\mathrm{fish}}$ is a vector of average variable fishing costs for SS, MS, and CP sectors, $\mathbf{c}_t^{\mathrm{proc}}$ is a vector of costs of processing a bundle of products (roe, fillet, surimi, and H&G), p_t^{fuel} is a monthly time series of fuel prices in Unalaska, $\mathbf{Dist}_t$ is a vector of the average distance from delivery port to the fishing grounds for vessels in the SS, MS, and CP sectors, $\mathbf{CPUE}_t$ is a vector of the average catch-per-day for vessels in the SS, MS, and CP sectors, $\mathbf{L}_t^{\mathrm{fish}}$ is a vector of the number of person-hours per trip for vessels in the SS, MS, and CP sectors, $\mathbf{L}_t^{\mathrm{proc}}$ is a vector of the number of person-hours employed in processing for vessels in the SS, MS, and CP sectors, p_t^{exv} is the transactions (ex-vessel) price for catcher vessel deliveries to shore-based processing plants or motherships, and p_t^{add} represents the costs of additives used by shore-based and at-sea processors in the formulation of surimi. Because the most common form of payment to labor is a share of adjusted gross revenues, fishing labor costs are modeled as a proportion of catch and ex-vessel price. Because costs are not fully integrated across sectors or product forms, the coefficient matrix, $\boldsymbol{\Theta}$, is sparse. The error vector, $\boldsymbol{\zeta}_t$, for Eq. (10) includes contemporaneous and serial correlations due to the technological connections between catching and processing, and relatedness between input factor costs across catching and processing sectors.

Total variable costs of catching and producing fillets, surimi, roe, and H&G pollock are calculated from the solution to Eqs. (6), (7), (8), and (10):

$$\mathrm{TC}_t = \mathbf{c}_t \mathbf{q}_t \tag{11}$$

Objective function

The overall objective for this fishery is to optimize the net present value (NPV) of catches over time:

$$\underset{wrt\,\mathbf{h}_t}{\mathrm{Max}}\,(\mathrm{NPV}) = \sum_{t=0}^{\infty} (1+\delta)^{-t} (\mathrm{TR}_t - \mathrm{TC}_t). \tag{12}$$

Where δ is discount rate and total revenue and total variable costs are defined in Eqs. (9) and (11).

Results

Model solutions

First order (necessary) conditions that characterize the optimization of Eq. (12) with respect to choices of catches of eastern Bering pollock and subject to the constraints described by Eqs. (1–11) depend on choices about the degree of cooperation between fisheries managers in the US and the Russian Federation, the nature of fishery governance, and the extent to which pollock stocks and input and output price vectors are interdependent. A few examples are illustrated below.

Scenario 1: Biologically and economically independent fisheries

For this simple scenario, it is assumed that input and output price vectors associated with US and Russian Federation pollock fisheries are independent and that the stocks are biologically separable along the US-Russian Federation Convention Line. In this case, the objective function (Eq. 12) is additively separable between the US and the Russian Federation and the constraining Eqs. (1–11) are block diagonal. For example, a block diagonal formulation of Eq. (1) is:

$$\begin{pmatrix} x_t^{se} \\ x_t^{nw} \\ \hline x_t^{rf} \end{pmatrix} = \begin{pmatrix} a_{01} \\ a_{02} \\ \hline a_{03} \end{pmatrix} + \left(\begin{array}{cc|c} a_{111} & a_{112} & 0 \\ a_{121} & a_{122} & 0 \\ \hline 0 & 0 & a_{133} \end{array}\right) \begin{pmatrix} x_{t-1}^{se} \\ x_{t-1}^{nw} \\ \hline x_{t-1}^{rf} \end{pmatrix} + \left(\begin{array}{cc|c} x_{t-1}^{se} & 0 & 0 \\ 0 & x_{t-1}^{nw} & 0 \\ \hline 0 & 0 & x_{t-1}^{rf} \end{array}\right) \left(\begin{array}{cc|c} a_{211} & a_{212} & 0 \\ a_{221} & a_{222} & 0 \\ \hline 0 & 0 & a_{233} \end{array}\right) \begin{pmatrix} x_{t-1}^{se} \\ x_{t-1}^{nw} \\ \hline x_{t-1}^{rf} \end{pmatrix} + \left(\begin{array}{cc|c} a_{311} & a_{312} & 0 \\ a_{321} & a_{322} & 0 \\ \hline 0 & 0 & a_{333} \end{array}\right) \begin{pmatrix} h_{t-1}^{se} \\ h_{t-1}^{nw} \\ \hline h_{t-1}^{rf} \end{pmatrix} + \left(\begin{array}{cc|c} a_{411} & a_{412} & 0 \\ a_{421} & a_{422} & 0 \\ \hline 0 & 0 & a_{433} \end{array}\right) \begin{pmatrix} r_t^{se} \\ r_t^{nw} \\ \hline r_t^{rf} \end{pmatrix} + \begin{pmatrix} \varepsilon_t^{se} \\ \varepsilon_t^{nw} \\ \hline \varepsilon_t^{rf} \end{pmatrix}. \tag{13}$$

From the perspective of the US, the problem is to choose sustainable harvest levels that maximize the net present value of the EBS pollock fishery:

$$\underset{wrt\,\mathbf{h}_t^{us}}{\text{Max}}\left(\text{NPV}^{us}\right) = \sum_{t=0}^{\infty}(1+\delta)^{-t}\left(\text{TR}_t^{us} - \text{TC}_t^{us}\right) = \sum_{t=0}^{\infty}(1+\delta)^{-t}\left(\text{TR}_t^{nw} + \text{TR}_t^{se} - \text{TC}_t^{nw} - \text{TC}_t^{se}\right) \tag{14}$$

Subject to:

$$\begin{pmatrix} x_t^{se} \\ x_t^{nw} \end{pmatrix} = \begin{pmatrix} a_{01} \\ a_{02} \end{pmatrix} + \begin{pmatrix} a_{111} & a_{112} \\ a_{121} & a_{122} \end{pmatrix}\begin{pmatrix} x_{t-1}^{se} \\ x_{t-1}^{nw} \end{pmatrix} + \begin{pmatrix} x_{t-1}^{se} & 0 \\ 0 & x_{t-1}^{nw} \end{pmatrix}\begin{pmatrix} a_{211} & a_{212} \\ a_{221} & a_{222} \end{pmatrix}\begin{pmatrix} x_{t-1}^{se} \\ x_{t-1}^{nw} \end{pmatrix} + \begin{pmatrix} a_{311} & a_{312} \\ a_{321} & a_{322} \end{pmatrix}\begin{pmatrix} h_{t-1}^{se} \\ h_{t-1}^{nw} \end{pmatrix} + \begin{pmatrix} a_{41} \\ a_{42} \end{pmatrix} r_t + \begin{pmatrix} \varepsilon_t^{se} \\ \varepsilon_t^{nw} \end{pmatrix} \tag{15}$$

$$\begin{pmatrix} \breve{x}_t^{se} \\ \breve{x}_t^{nw} \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}\begin{pmatrix} x_t^{se} \\ x_t^{nw} \end{pmatrix} + \begin{pmatrix} \upsilon_t^{se} \\ \upsilon_t^{nw} \end{pmatrix} \tag{16}$$

$$\begin{pmatrix} r_t^{se} \\ r_t^{nw} \end{pmatrix} = \begin{pmatrix} \lambda_{011} & \lambda_{012} \\ \lambda_{021} & \lambda_{022} \end{pmatrix}\begin{pmatrix} \breve{x}_{t-l}^{se} \\ \breve{x}_{t-l}^{nw} \end{pmatrix} + \begin{pmatrix} \breve{x}_{t-l}^{se} & 0 \\ 0 & \breve{x}_{t-l}^{nw} \end{pmatrix}\begin{pmatrix} \lambda_{111} & \lambda_{112} \\ \lambda_{121} & \lambda_{122} \end{pmatrix}\begin{pmatrix} \breve{x}_{t-l}^{se} \\ \breve{x}_{t-l}^{nw} \end{pmatrix} + \begin{pmatrix} \eta_t^{se} \\ \eta_t^{nw} \end{pmatrix} \tag{17}$$

$$\begin{gathered}\left(\varepsilon_t^{se} \quad \varepsilon_t^{nw} \quad \upsilon_t^{se} \quad \upsilon_t^{nw} \quad \eta_t^{se} \quad \eta_t^{nw} \quad \mathbf{Env}_t\right)' = \Gamma\mathbf{z}_t + \mathbf{e}_t \\ \mathbf{z}_{t+1} = \Theta\mathbf{z}_t + \Phi\mathbf{e}_t\end{gathered} \tag{18}$$

$$h_t^{us} = h_t^{nw} + h_t^{se} \le \breve{h}_{\text{MSY}}^{us} \tag{19}$$

$$\mathbf{q}_t^{us} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1\mathbf{p}_t^{us} + \boldsymbol{\beta}_2\mathbf{p}_{t-1}^{us} + \boldsymbol{\beta}_3\mathbf{q}_{t-k}^{us} + \boldsymbol{\beta}_4\mathbf{m}_t + \mathbf{u}_t \tag{20}$$

$$\mathbf{p}_t^{us} = \boldsymbol{\gamma}_0 + \boldsymbol{\Gamma}_1\mathbf{q}_t^{us} + \boldsymbol{\Gamma}_2\mathbf{p}_t^{us} + \boldsymbol{\Gamma}_3\mathbf{p}_{t-1}^{us} + \boldsymbol{\Gamma}_4\mathbf{p}_t^{sub} + \boldsymbol{\Gamma}_5\mathbf{Inv}_{t-1}^{us} + \boldsymbol{\Gamma}_6\mathbf{Inc}_t + \boldsymbol{\Gamma}_7\mathbf{Exch}_t + \boldsymbol{\Gamma}_8\mathbf{m}_t + \boldsymbol{\xi}_t \tag{21}$$

$$\mathbf{q}_t^{us} = \omega\mathbf{h}_t^{us} \tag{22}$$

$$\ln\left(\mathbf{c}_t^{us}\right) = \Theta\mathbf{C}_t^{us} + \boldsymbol{\zeta}_t^{us} \tag{23}$$

From the perspective of the US, the first order conditions for the maximization of sustainable net revenues are:

$$\text{MR}_t^{us} = \frac{\partial\text{TR}_t^{us}}{\partial h_t^{us}} = \frac{\partial\text{TC}_t^{us}}{\partial h_t^{us}} = \text{MC}_t^{us} \text{ and } \frac{\partial\left(x_t^{se} + x_t^{nw}\right)}{\partial t} = 0,$$

where marginal revenue to US fishermen, MR_t^{us}, is the change in total revenue that would accrue to US fishermen from a small increment in catch by US fishermen in time t. Similarly, the marginal change in total cost to US firms to catch and process a small increment of catch in time t is denoted MC_t^{us}.

Because costs and revenues differ by region, the optimal level of catch from each region is obtained from the solution to:

$$\frac{\partial\text{TR}_t^{us}}{\partial h_t^{se}} - \frac{\partial\text{TC}_t^{us}}{\partial h_t^{se}} = 0 = \frac{\partial\text{TR}_t^{us}}{\partial h_t^{nw}} - \frac{\partial\text{TC}_t^{us}}{\partial h_t^{nw}}.$$

That is, total harvests should be divided between the two regions such that marginal net revenues to the US are equalized. The rule for allocating catch across regions extends to the allocation of catch between sectors within regions and vessels within sectors. That is, a characteristic of the optimal solution is that the marginal net revenue to each vessel in each sector in each region is equal.

For the Russian Federation, the optimization problem is to choose a harvest level that maximizes net present value:

$$\underset{wrt\,h_t^{rf}}{\text{Max}}\left(\text{NPV}^{rf}\right) = \sum_{t=0}^{\infty}(1+\delta)^{-t}\left(\text{TR}_t^{rf} - \text{TC}_t^{rf}\right) \tag{24}$$

Subject to:

$$x_t^{rf} = a_{03} + a_{133}x_{t-1}^{rf} + x_{t-1}^{rf}a_{233}x_{t-1}^{rf} + a_{333}h_{t-1}^{rf} + a_{433}r_t^{rf} + \varepsilon_t^{rf} \tag{25}$$

$$\breve{x}_t^{rf} = b_{33}x_t^{rf} + \upsilon_t^{rf} \tag{26}$$

$$r_t^{rf} = \lambda_{033}\,\breve{x}_{t-l}^{rf} + \breve{x}_{t-l}^{rf}\,\lambda_{133}\breve{x}_{t-l}^{rf} + \eta_t^{rf} \tag{27}$$

$$\begin{gathered}\left(\boldsymbol{\varepsilon}_t^{rf} \quad \boldsymbol{\upsilon}_t^{rf} \quad \boldsymbol{\eta}_t^{rf} \quad \mathbf{Env}_t\right)' = \Gamma\mathbf{z}_t + \mathbf{e}_t \\ \mathbf{z}_{t+1} = \Theta\mathbf{z}_t + \Phi\mathbf{e}_t\end{gathered} \tag{28}$$

$$h_t^{rf} = \alpha^{rf}x_t^{rf} \tag{29}$$

$$\mathbf{q}_t^{\mathrm{rf}} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1\mathbf{p}_t^{\mathrm{rf}} + \boldsymbol{\beta}_2\mathbf{p}_{t-1}^{\mathrm{rf}} + \boldsymbol{\beta}_3\mathbf{q}_{t-k}^{\mathrm{rf}} + \boldsymbol{\beta}_4\mathbf{m}_t + \mathbf{u}_t \tag{30}$$

$$\mathbf{p}_t^{\mathrm{rf}} = \boldsymbol{\gamma}_0 + \boldsymbol{\Gamma}_1\mathbf{q}_t^{\mathrm{rf}} + \boldsymbol{\Gamma}_2\mathbf{p}_t^{\mathrm{rf}} + \boldsymbol{\Gamma}_3\mathbf{p}_{t-1}^{\mathrm{rf}} + \boldsymbol{\Gamma}_4\mathbf{p}_t^{\mathrm{sub}} + \boldsymbol{\Gamma}_5\mathbf{Inv}_{t-1}^{\mathrm{rf}} + \boldsymbol{\Gamma}_6\mathbf{Inc}_t + \boldsymbol{\Gamma}_7\mathbf{Exch}_t + \boldsymbol{\Gamma}_8\mathbf{m}_t + \boldsymbol{\xi}_t \tag{31}$$

$$\mathbf{q}_t^{\mathrm{rf}} = \omega\mathbf{h}_t^{\mathrm{rf}} \tag{32}$$

$$\ln\left(\mathbf{c}_t^{\mathrm{rf}}\right) = \Theta\mathbf{C}_t^{\mathrm{rf}} + \boldsymbol{\zeta}_t^{\mathrm{rf}}. \tag{33}$$

The first order conditions that characterize a sustainable optimal solution are:

$$\mathrm{MR}_t^{\mathrm{rf}} = \frac{\partial \mathrm{TR}_t^{\mathrm{rf}}}{\partial h_t^{\mathrm{rf}}} = \frac{\partial \mathrm{TC}_t^{\mathrm{rf}}}{\partial h_t^{\mathrm{rf}}} = \mathrm{MC}_t^{\mathrm{rf}} \text{ and } \frac{\partial x_t^{\mathrm{rf}}}{\partial t} = 0.$$

Solving these first order conditions provides estimates of the optimal sustainable harvest, h_t^{rf}, and corresponding optimal sustainable biomass, x_t^{rf}. Again, this solution anticipates that catch will be allocated among sectors and vessels such that marginal net revenues are equalized.

While these results assume independent stocks and independent input and output price vectors, they are linked if there is contemporaneous or intertemporal correlation in the environmental forcing variables. By itself, that linkage would not lead to excessive harvest levels, but it would suggest that modeling the system as a whole would lead to improved estimates of coefficients representing pollock stock dynamics in US and Russian Federation waters. If, in fact, the EBS pollock form a single stock that encompasses fish harvested in Russian Federation waters east of 170°E, this scenario could result in excessive harvests. Similarly, if input or output price vectors are interdependent, this solution will be economically suboptimal. Moreover, if the structure of fisheries governance prevents reallocation of catch among vessels and between sectors, the total net benefits produced will be less than the maximum that could be produced [9].

Scenario 2: Interdependent stocks with interdependent input and output prices: joint optimization

For this scenario, the constraining assumptions of the first scenario are fully relaxed. That is, it is assumed that EBS pollock form a single stock that is exploited by US and Russian Federation fisheries, that the products of these fisheries are sold into a global output market, and that inputs needed to prosecute these fisheries are purchased from a global input market. It is further assumed that the US and Russian Federation coordinate pollock harvests to maximize the total net present value across all fisheries that harvest EBS pollock:

$$\underset{wrt\, h_t}{\mathrm{Max}}\,(\mathrm{NPV}) = \sum_{t=0}^{\infty}(1+\delta)^{-t}(\mathrm{TR}_t - \mathrm{TC}_t), \tag{34}$$

subject to the constraints represented by Eqs. (1–4, 5a, 5b, 6–8, and 10) and $\mathbf{h}_t = \mathbf{h}_t^{\mathrm{rf}} + \mathbf{h}_t^{\mathrm{us}}$. The first order conditions are:

$$\mathrm{MR}_t = \frac{\partial \mathrm{TR}}{\partial h_t} = \frac{\partial \mathrm{TC}}{\partial h_t} = \mathrm{MC}_t, \text{ and } \frac{\partial\left(x_t^{\mathrm{se}} + x_t^{\mathrm{nw}} + x_t^{\mathrm{rf}}\right)}{\partial t} = 0.$$

Because net revenues differ by region, the optimal solution will divide the optimal sustainable harvest among the regions such that marginal net revenues are equalized:

$$\frac{\partial \mathrm{TR}_t}{\partial h_t^{\mathrm{se}}} - \frac{\partial \mathrm{TC}_t}{\partial h_t^{\mathrm{se}}} = \frac{\partial \mathrm{TR}_t}{\partial h_t^{\mathrm{nw}}} - \frac{\partial \mathrm{TC}_t}{\partial h_t^{\mathrm{nw}}} = \frac{\partial \mathrm{TR}_t}{\partial h_t^{\mathrm{rf}}} - \frac{\partial \mathrm{TC}_t}{\partial h_t^{\mathrm{rf}}} = 0.$$

The key difference between this example and the preceding example is that the optimal level of harvest in each region depends on its effect on net revenues to the combined US and Russian Federation fisheries rather than the effect on each nation alone. Again, for an optimal solution, the marginal net benefits need to be equated across vessels and sectors as well as regions, and institutional barriers to such transfers will lead to suboptimality.

Setting out to maximize the total sustainable value of the EBS pollock resource accounts for stock relatedness and the integration of global markets for pollock products and input factors. The solution to this scenario generates the maximum possible net present value from the sustainable harvest of EBS pollock fisheries as a whole. Under this scenario, the optimum level of total pollock harvests is lower and the biomass that sustains those harvests is higher than under any other scenario. Because this scenario maximizes total net revenues without regard to whether they accrue to US or Russian Federation fishermen, it will likely be necessary for regions (and sectors and vessels) that are allocated increased TACs to make side payments to regions (and sectors and vessels) that are allocated smaller TACs.

Scenario 3: Interdependent stocks with interdependent input and output prices: independent optimization

As in scenario 2, it is assumed for this scenario that EBS pollock form a single stock that is exploited by US and Russian Federation fisheries. The products of these fisheries are assumed to be sold into a global output market and the inputs needed to prosecute these fisheries are assumed to be purchased from a global input market. However, as in scenario 1, it is assumed that the US and Russian Federation act independently to optimize harvests of pollock. In setting optimal harvest limits, they may ignore each other (quasi-competitive solution), they may account for catch levels that each would set if it ignored the catch levels the other set (Cournot solution) or they may account for catch levels that each would set in anticipation of catch levels the other would set (Stackelberg solution). This scenario approximates the status quo except that EBS pollock is treated as a single stock throughout its range in US and

Russian Federation waters and the interdependencies of input and output price vectors are considered in the selection of harvest limits.

As in scenario 1, the US sets harvest limits to:

$$\underset{wrt\,\mathbf{h}_t^{us}}{\mathrm{Max}}\left(\mathrm{NPV}^{us}\right)=\sum_{t=0}^{\infty}(1+\delta)^{-t}\left(\mathrm{TR}_t^{us}-\mathrm{TC}_t^{us}\right) \tag{35}$$

However, as in scenario 2, the constraint set is full versions of Eqs. (1–4, 5b, 6–8, and 10). The first order conditions for the US for this scenario are similar to those in scenario 1 except that MR^{us} takes into account the influence of Russian Federation catches on product prices and MC^{us} takes into account the influence of Russian Federation catches on input factor costs:

$$\left.\begin{array}{l} 0=\dfrac{\partial \mathrm{TR}_t^{us}}{\partial h_t^{se}}-\dfrac{\partial \mathrm{TC}_t^{us}}{\partial h_t^{se}} \\ 0=\dfrac{\partial \mathrm{TR}_t^{us}}{\partial h_t^{nw}}-\dfrac{\partial \mathrm{TC}_t^{us}}{\partial h_t^{nw}} \end{array}\right|\mathrm{TR}_t^{us}=f\left(h_t^{se},h_t^{nw},h_t^{rf}\right)$$

$$\text{and } \mathrm{TC}_t^{us}=g\left(h_t^{se},h_t^{nw},h_t^{rf}\right)$$

In addition, sustainability requires that

$$\frac{\partial\left(x_t^{se}+x_t^{nw}+x_t^{rf}\right)}{\partial t}=0.$$

For the Russian Federation, the objective is to:

$$\underset{wrt\,h_t^{rf}}{\mathrm{Max}}\left(\mathrm{NPV}^{rf}\right)=\sum_{t=0}^{\infty}(1+\delta)^{-t}\left(\mathrm{TR}_t^{rf}-\mathrm{TC}_t^{rf}\right), \tag{36}$$

subject to the full versions of Eqs. (1–4, 5a, 6–8, and 10). The first order conditions for the Russian Federation are also similar to those in the first scenario except that MR^{rf} takes into account the influence of US catches on product prices and MC^{rf} takes into account the influence of US catches on input factor costs and the first order condition for sustainability accounts for the status of EBS pollock throughout its range:

$$0=\left.\frac{\partial \mathrm{TR}_t^{rf}}{\partial h_t^{se}}-\frac{\partial \mathrm{TC}_t^{rf}}{\partial h_t^{se}}\right|\mathrm{TR}_t^{rf}=f\left(h_t^{se},h_t^{nw},h_t^{rf}\right)$$

$$\text{and } \mathrm{TC}_t^{rf}=g\left(h_t^{se},h_t^{nw},h_t^{rf}\right),$$

and

$$\frac{\partial\left(x_t^{se}+x_t^{nw}+x_t^{rf}\right)}{\partial t}=0.$$

The solutions to these first order conditions differ from the solutions under scenario 1. Accounting for stock biogeography and for market inter-relatedness leads the US and Russian Federation to select lower harvest levels than would be selected if markets were not integrated and the stock was not shared. While solutions to this scenario avoid the risk of overharvesting that exists under scenario 1, they may approach but will not achieve the magnitude of sustainable net present value reached under scenario 2 because harvest decisions by the US and Russian Federation are independently optimal but not jointly optimal. Moreover, the actual magnitude of net present value will be reduced if there are institutional barriers to the transfer of catch rights between vessels or sectors.

Discussion

Many commercially important fish stocks are transboundary or highly migratory. Climate-induced shifts in the distribution of these species will change the portion of each stock that is exposed to fishing in different parts of its range [6, 27]. Long-standing agreements, whether explicit or implicit, for shared stocks may be disrupted [16, 17, 28], reopening questions about which nations are entitled to what shares of particular stocks of fish. In this paper, it has been shown that the optimal harvest strategy from the perspective of individual nations differs from the optimal harvest strategy from the perspective of the whole fishery. This outcome is well known from the management of petroleum fields — in order to maximize total value, let a single authority determine the optimum number and placement of wells and settle on an agreement to share the net earnings of those wells [29, 30]. Similar outcomes have been shown in fisheries within national fishing zones. For example, faced with low revenues, overcapitalization, and a derby style fishery, fishermen in the Chignik, sockeye salmon fishery formed a cooperative agreement under which more than half the fleet agreed not to fish in return for receiving a share of the net revenues of those vessels that did engage in the fishery [31]. This agreement did not change the total number of fish caught, but nearly halved the cost of catching those fish [32]. Similarly, formation of cooperatives within the US EBS pollock fishery was accompanied by a fifty-percent reduction in the number of vessels in the catcher-processor sector, a thirty-percent reduction in the number of vessels delivering to shore-based processors, a lengthening of the duration of the fishery (especially during the summer-fall season), and a near doubling of the product recovery rate [11].

As suggested by the scenarios presented in this paper, unitized management of transboundary and highly migratory fish stocks would go beyond current bilateral and regional fisheries management agreements that focus of dividing the physical quantities of fish and would instead maximize the total value of catches and then allocate the value between nations. Moreover, to extract the greatest possible sustainable net economic value from the fishery, it is necessary to establish a mechanism that will allow catches to be allocated among vessels, sectors, and regions such that marginal net value is equalized. In the case of groundwater resources, it has been shown that a system of transferable property rights can achieve outcomes similar to those achieved through unitized basin management but without the high information requirements needed for unitized basin management [33, 34]. By analogy, defining individual transferable quotas that pertain to each transboundary fish stock throughout its range could be expected to generate total net benefits comparable to those achievable under joint optimization of the net present value of sustainable catches from the whole stock (scenario 2). That is, in theory, the maximum net present value of sustainable harvests of EBS pollock could be realized either through negotiated agreements between the US and the Russian Federation predicated on solution of the model described in scenario 2, or through creation of an individual transferable quota system (or by extending the existing AFA-Cooperative system) to include catches of EBS pollock in the US EEZ as well as in the Russian Federation EEZ east of 170°E.

Experience with the actual management of groundwater basins is also instructive. If externalities such as pollution are present, if there is heterogeneity in the extent to which groundwater applied to agricultural lands contributes to recharge of the basin, or if there is market concentration, a market based solution is unlikely to achieve the maximum theoretically possible level of benefits and may or may not exceed the benefits that could be secured under a central planning approach [35, 36]. The problem of unitized management of oil fields is made easier because petroleum from a basin is an undifferentiable product that is sold as a commodity to refiners — even though landowners who hold petroleum rights may differ from one another, their motivation and economic opportunities are similar. By contrast, those who hold rights to extract groundwater may do so for agricultural, industrial, or municipal purposes with very different demand functions, very different sensitivities to externalities, and very different risk profiles. Even within these sectors, heterogeneity can be very pronounced — grain farmers, orchard farmers, vegetable farmers, and livestock operators may not easily agree on pricing and allocation rules needed for the smooth function of a market-based groundwater rights system. Management of a transboundary fishery more closely resembles management of a groundwater basin than it does management of an oil field. Fishermen and fishing nations are heterogeneous in productive technology and in objectives. Fish resources have values to society (e.g., employment, food security, economic development, culture, and support for coastal communities) that cannot be reified in a simple measure of net present value. To the extent that these issues are particularly important relative to the importance of net revenues, a negotiated central planning approach may be superior to a fully market-based approach to management of transboundary fish resources.

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